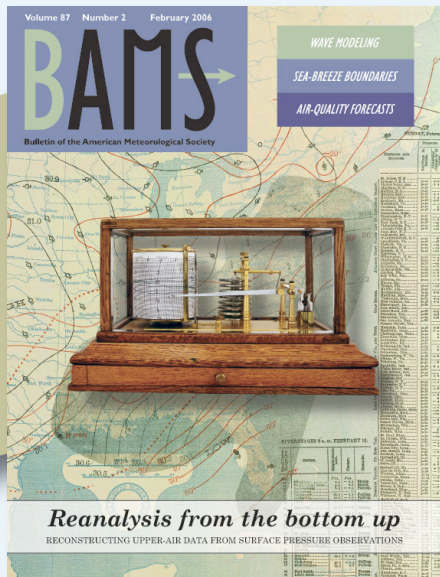


Climate System Observations and Analysis



Gilbert P. Compo

Historical Reanalysis



US and International Calls for Historical Reanalyses

Reanalysis datasets “spanning the instrumental record”
(WCRP 3rd conference on reanalysis, 2008)

- Group on Earth Observations/GCOS Task CL-06-01 **Sustained Reprocessing and Reanalysis Efforts**
- U.S. GCRP Revised Strategic Plan (2008)
Goal 3 Reduce uncertainty in projections of how the Earth’s climate and environmental systems may change in the future
Key research topics: **Creating a Historical Reanalysis of the Atmosphere of the 20th Century**
- NOAA Strategic plan (2006-2011) to meet NOAA and GCRP goals calls for integrated observations and analysis with “**quantified uncertainties**”.
- Emphasis on reanalysis improvements for understanding multidecadal variability of **weather extremes** and variations (e.g., CCSP, 2008, Weather and Climate Extremes SAP3.3)



Some Uses of Historical Reanalyses

1. Effectively doubling the reanalysis record length 😊
2. Climate model validation dataset for large-scale synoptic anomalies during extreme periods, such as droughts (30's, 50's).
3. Better understand events such as the 1920-1940's Arctic warming.
4. Determining storminess and storm track variations over last 100-150 years.
5. Developing new forecast products predicting changes in frequency and intensity of weather extremes, e.g., cold air outbreaks, severe storms.
6. Developing and improving forecasts of low-frequency (e.g., Pacific-North America pattern, North Atlantic Oscillation) atmospheric variations and their interannual to decadal variability.
7. Understanding changing atmospheric background state associated with interdecadal hurricane activity.
8. Homogenizing upper-air and other independent observations.
9. Estimating historical probability distributions for wind energy.
10. Estimating risks of extreme events for insurance and re-insurance.



Challenges to Meeting National and International Goals for Historical Reanalyses

- Satellite network only back to 1970's, Upper-air network comprehensive only back to 1940's, scant to non-existent in 19th century
- 3-D Var data assimilation systems such as used in NCEP-NCAR, NCEP-DOE, ERA-40 reanalyses depends on upper-air data for high quality upper-level fields (*Bengtsson et al. 2004, Kanamitsu and Hwang 2005*).
- However, studies using advanced data assimilation methods (e.g., 4D-Var, Ensemble Filter) suggest surface network, especially surface pressure observations, could be used to generate high-quality upper-air fields (*Bengtsson 1980, Thépaut and Simmons 2003, Thépaut 2006, Whitaker et al. 2003, 2004, 2009, Anderson et al. 2005, Compo et al. 2006*).
- Surface Pressure observations are consistent and reliable throughout 20th Century and provide dynamical information about the full atmospheric column.



The Twentieth Century Reanalysis Project

Summary: An international collaborative project led by NOAA and CIRES to produce high-quality tropospheric reanalyses for the last 100+ years *using only surface observations*.

The reanalyses will provide:

- First-ever estimates of near-surface and tropospheric 6-hourly fields extending back to the beginning of the 20th century;
- Estimates of biases and uncertainties in the basic reanalyses;
- Estimates of biases and uncertainties in derived quantities (storm tracks, etc.)

Initial product will have higher quality in the Northern Hemisphere than in the Southern Hemisphere.

US Department of Energy INCITE computing award and NOAA Climate Goal support to complete 1871-2008 in 2010.

Initially produce 1908-1958.



Ensemble Filter Algorithm

Analysis x^a is a weighted average of the first guess x^b and observation y^o

$$x^a = (I - KH)x^b + Ky^o$$

Algorithm uses an ensemble to produce the weight K that varies with the atmospheric flow and the observation network

y^o is *only* surface pressure,

Hx^b is guess surface pressure

x is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints.

Using 56 member Ensemble

HadISST monthly boundary conditions (*Rayner et al. 2003*)

Version 1: T62 (about 2 degree), 28 level NCEP CFS03 model

Version 2: T62 , 28 level NCEP GFS08ex model

- time-varying CO₂, solar and volcanic radiative forcing



International Surface Pressure Databank (ISPD)

Subdaily observations assembled by
GCOS AOPC/OOPC Working Group on Surface Pressure (co-convenors, R. Allan and G. Compo)
GCOS/WCRP Working Group on Observational Data Sets for Reanalysis (convenor R. Vose)
Atmospheric Circulation Reconstructions over the Earth (ACRE)
NOAA NCDC, NOAA ESRL, and CU/CIRES: merging station data
NOAA ESRL and NCAR (ICOADS): merging marine data

Thank you to organizations contributing observations:

All Union Research Institute of Hydrometeorological
Information WDC

ACRE

Australian Bureau of Meteorology

British Antarctic Survey

Danish Meteorological Institute

Deutscher Wetterdienst

EMULATE

Environment Canada

ETH-Zurich

GCOS AOPC/OOPC WG on Surface Pressure

Hong Kong Observatory

IBTRACS

ICOADS

Instituto Geofisico da Universidade do Porto

IEDRO

Japanese Meteorological Agency

Jersey Met Dept.

KNMI

MeteoFrance

MeteoFrance – Division of Climate

Meteorological and Hydrological Service, Croatia

National Center for Atmospheric Research

Nicolaus Copernicus University

NOAA Climate Database Modernization Program

NOAA Earth System Research Laboratory

NOAA National Climatic Data Center

NOAA National Centers for Environmental Prediction

NOAA Northeast Regional Climate Center at Cornell U.

NOAA Midwest Regional Climate Center at UIUC

Norwegian Meteorological Institute

Ohio State U. – Byrd Polar Research Center

Portuguese Meteorological Institute (IM)

Proudman Oceanographic Laboratory

SIGN - Signatures of environmental change in the observations of
the Geophysical Institutes

South African Weather Service

UK Met Office Hadley Centre

U. of Colorado-CIRES/Climate Diagnostics Center

U. of East Anglia-Climatic Research Unit

U. of Lisbon-Instituto Geofisico do Infante D. Luiz

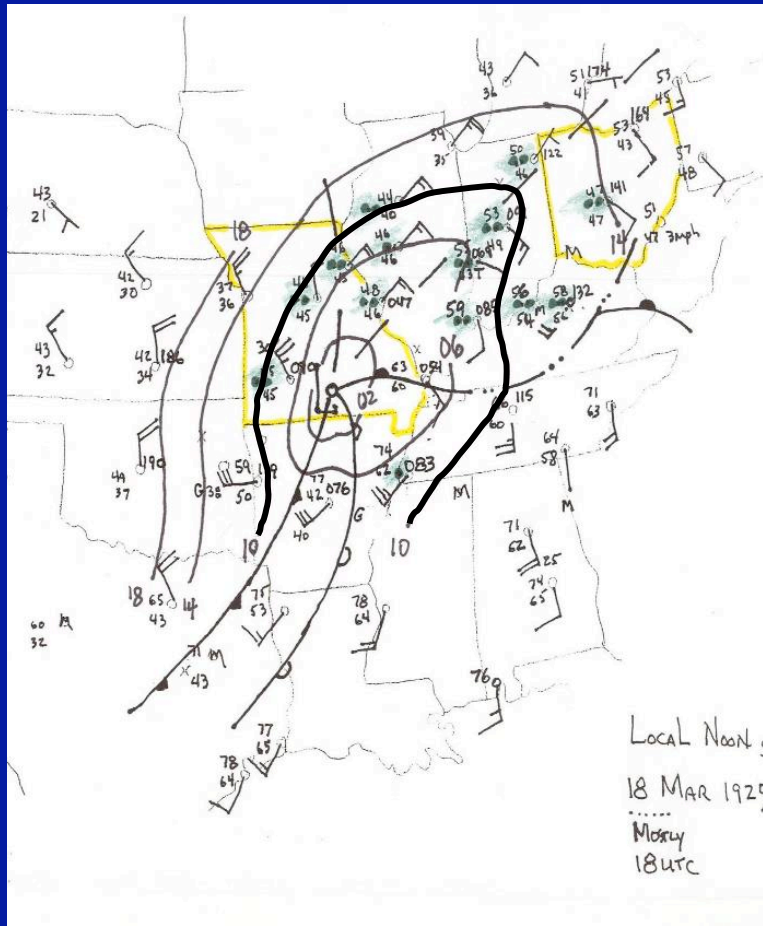
U. of Milan-IFGA

U. Rovira i Virgili-CCRG

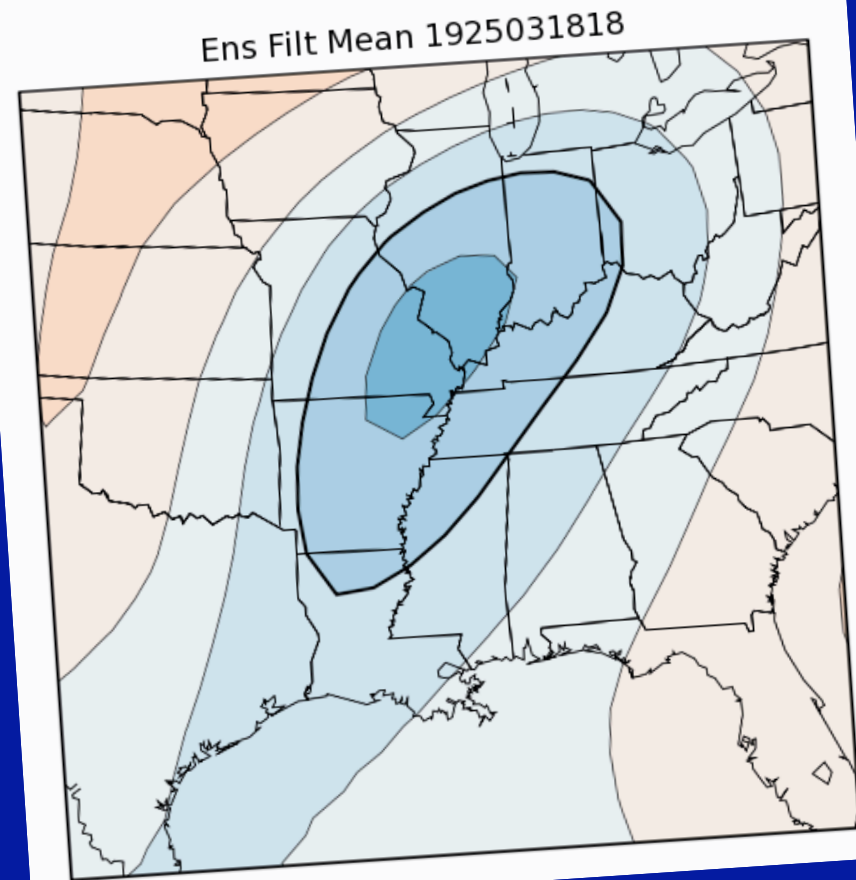
ZAMG



Sea Level Pressure Analyses for Tri-State Tornado Outbreak of 18 March 1925 (Deadliest Tornado in U.S. History)



Manual Analysis, courtesy R. Maddox

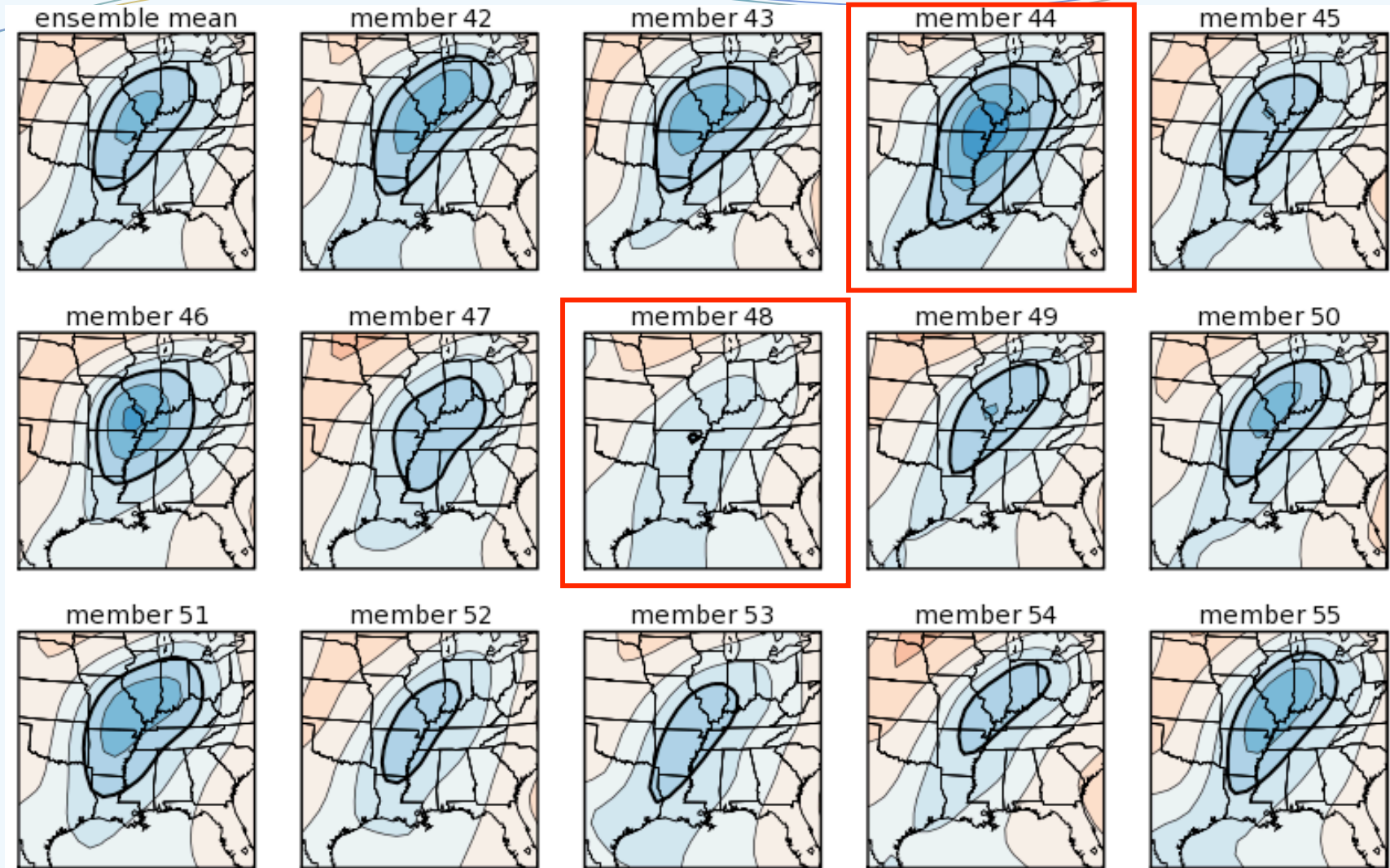


Ensemble mean from Ensemble Filter
(4 hPa interval, 1010 hPa thick)

NOTE!!! This analysis did not use ANY of the observations shown on the left.



Range of Possibilities for Sea Level Pressure 18 March 1925 18Z using 14 (of 56) Members

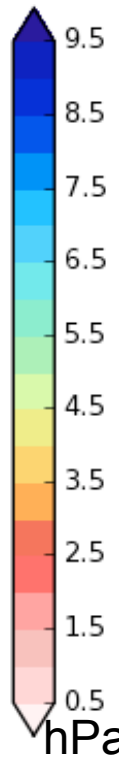
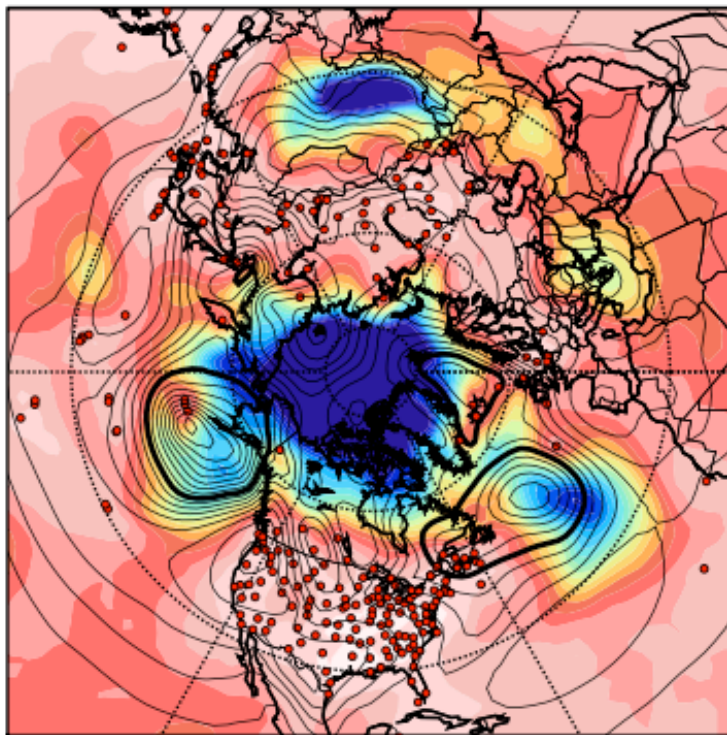


Ensemble of 56 possible realizations consistent with the observations

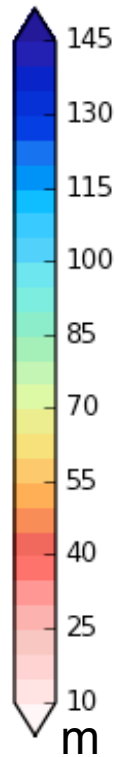
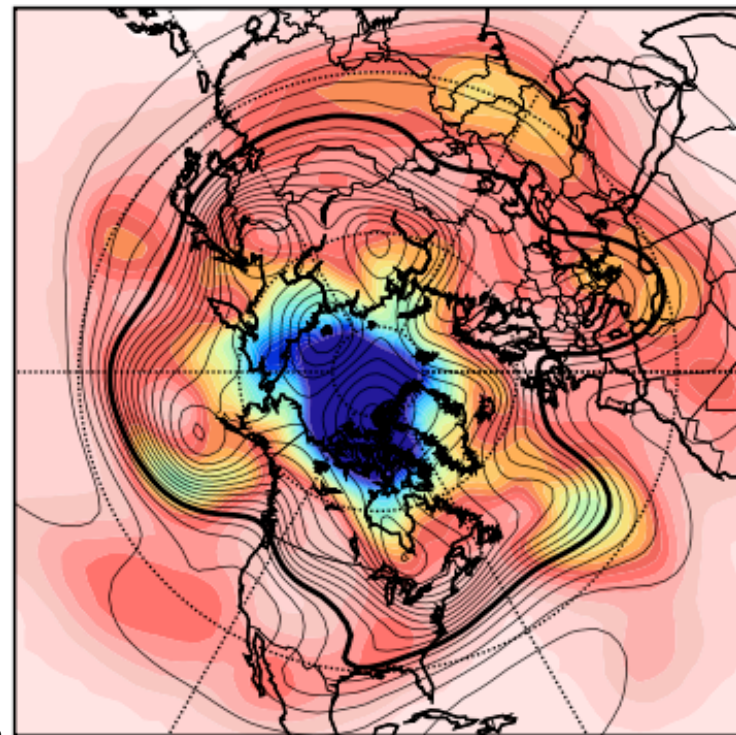


Analysis Ensemble Mean and Spread on 1 December 1918 00UTC

SLP



500 hPa GPH



Sea Level Pressure

Contours- ensemble mean

Shading- blue: more uncertain, white: more certain

500 hPa Geopotential Height

Uncertainty varies with the observation network and the atmospheric flow.



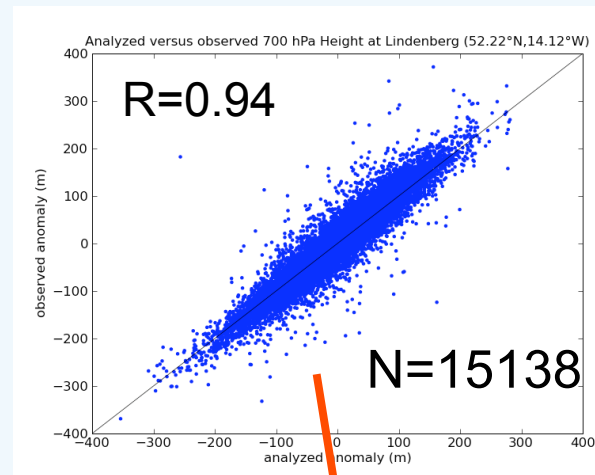


Local Anomaly Correlation of Twentieth Century Reanalysis and Upper-Air Geopotential Height Observations from Radiosondes and Other Platforms

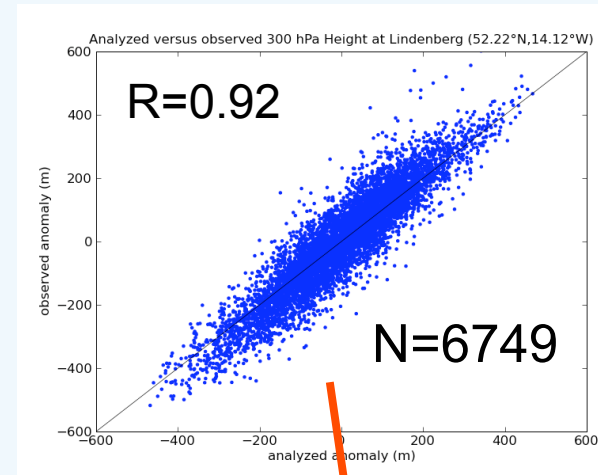
1908-1958
data from kites,
aircraft,
radiosondes
at Lindenberg,
Germany

Upper-air
observations
with at least
730 ascents
*Courtesy
ETH Zurich*

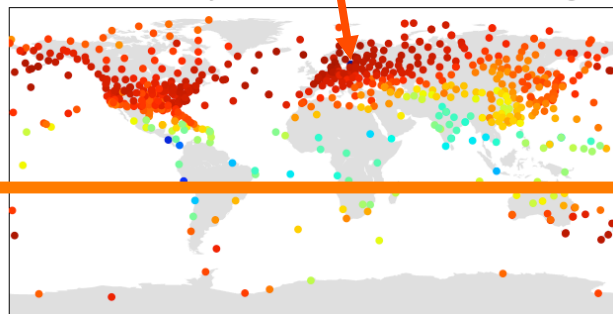
700 hPa



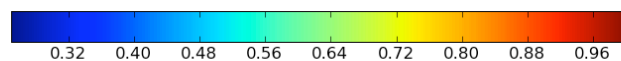
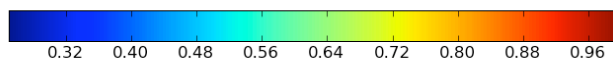
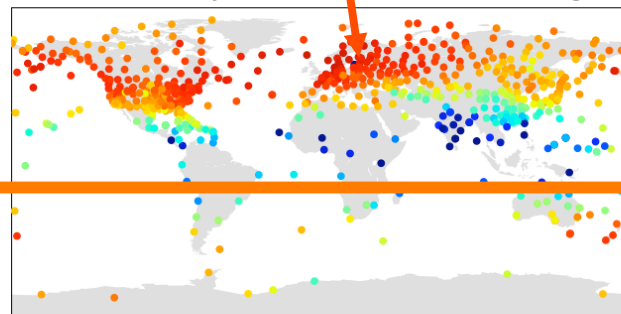
300 hPa



Correlation of Analyses with Radiosondes (700 hPa Height)



Correlation of Analyses with Radiosondes (300 hPa Height)

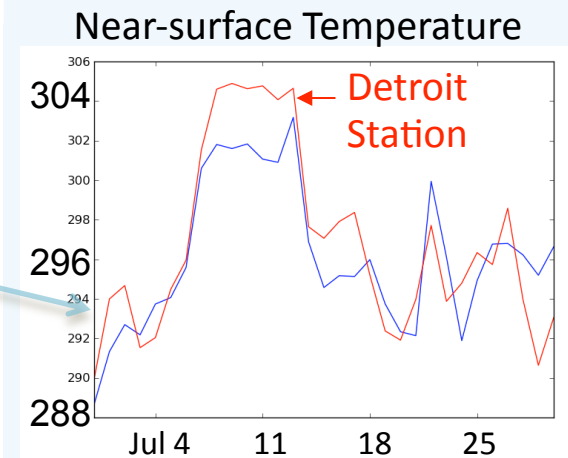
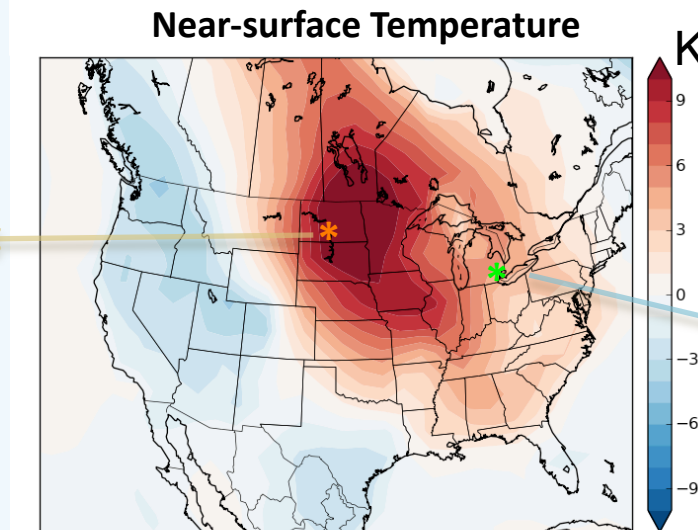
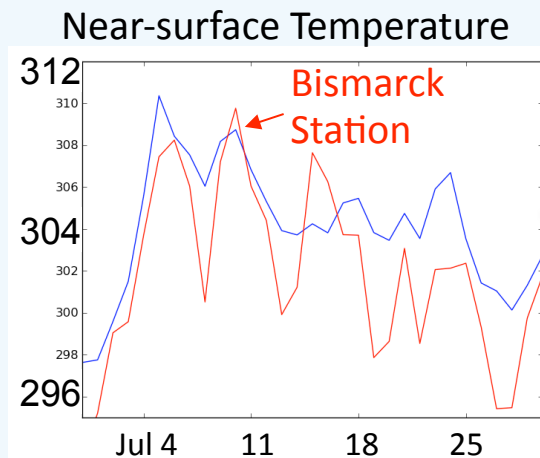
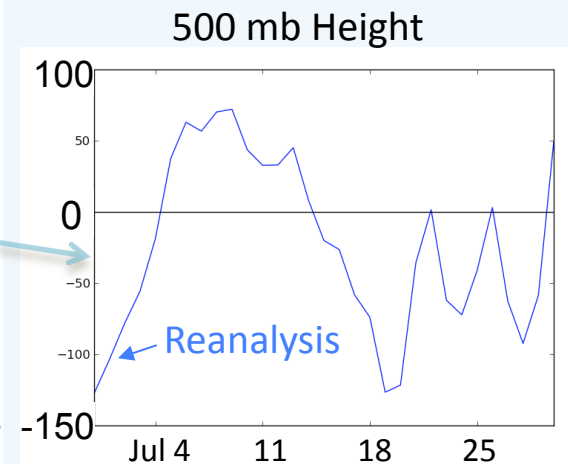
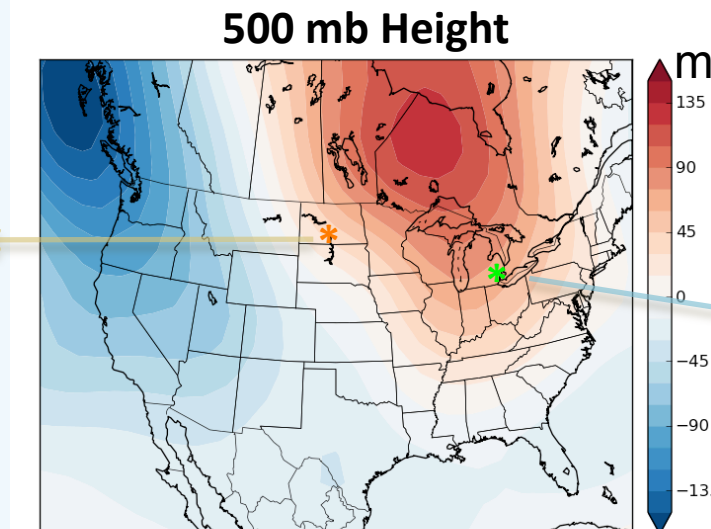
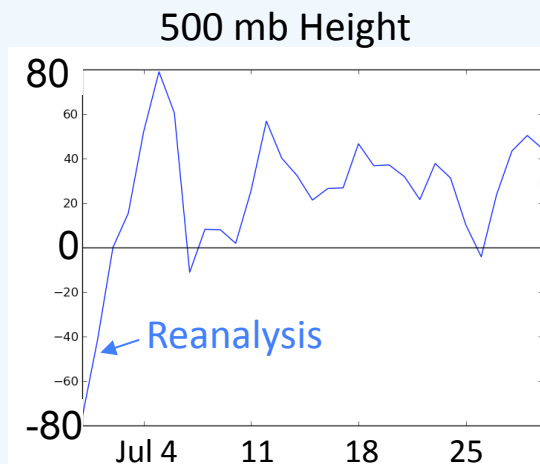


Agreement with Southern Hemisphere extratropics is good.



July 1936 North American Heat Wave

(1,000+ US & 1,000+ Canadian deaths during 14-day span)



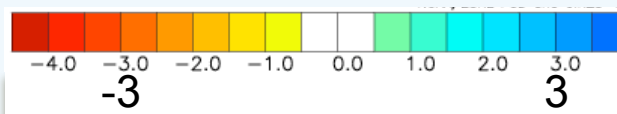
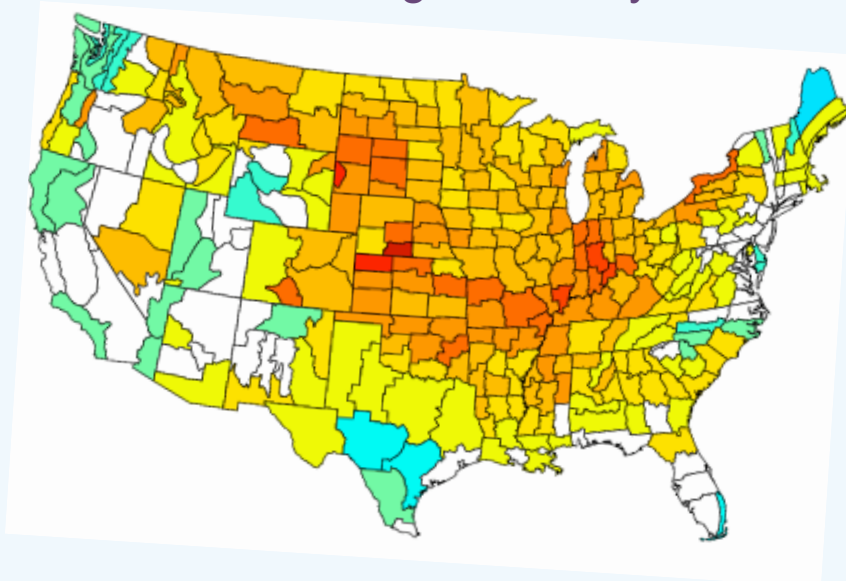
20th Century Reanalysis version 2
Anomalies July 8 – 14 with respect to 1891-2007



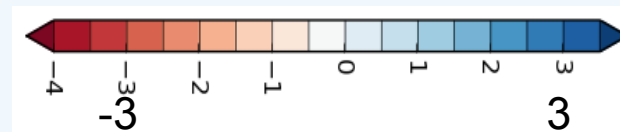
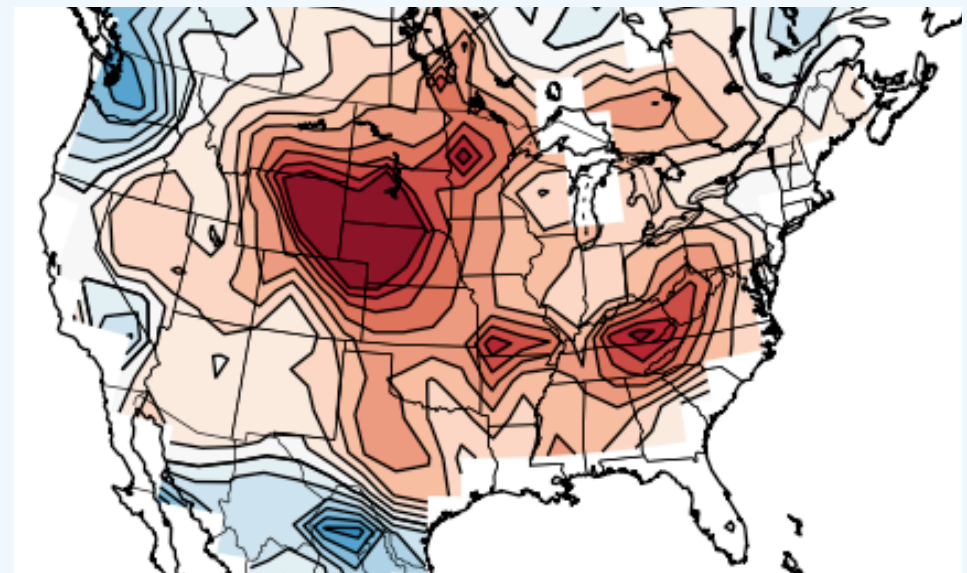
U.S Dust Bowl (July 1936)

Standardized monthly anomalies relative to 1961-1990

US Climate Division
Palmer Drought Severity Index



20CRv2 Soil Moisture 0-200 cm



Using only surface pressure, 20CR v2 appears to capture expected features even in derived quantities.



Historical Reanalysis Status and Plans

20th Century Reanalysis Project http://www.esrl.noaa.gov/psd/data/20thC_Rean

- Data Access: Analyses and ISPD (with feedback) will be freely available from NCAR, NOAA/ESRL and NOAA/NCDC.
- **Spring 2009:** Version 1, 1908-1958 (complete)
 - http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_Rean.html (NOAA ESRL)
 - <http://dss.ucar.edu/datasets/ds131.0> (NCAR)
- **Spring 2010:** Version 2, 1871-2008 (including time-varying CO2, aerosols, upgraded GFS from NCEP). **1891-2008 online now.**
 - http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html (NOAA ESRL)
 - <http://dss.ucar.edu/datasets/ds131.1> (NCAR)
 - <http://nomads.ncdc.noaa.gov> (NOAA NCDC, coming soon)
 - Coordinate with PCMDI CMIP5 distribution and validation for IPCC AR5

ECMWF Reanalysis Archive-Climate (ERA-CLIM)

- Series of reanalyses, including Surface-observation based back to 1900 (ERA-P1).
- ERA-P1: T159 spectral (~125km grid spacing) 60 layers in the vertical, extending upward to 0.1 hPa (approximately 65km altitude)
- **ERA-P1: Available 2012** (Contingent on EU funding)



Advances and Improvements towards

Surface Input Reanalysis for Climate Applications (SIRCA)

spanning 19th-21st centuries over the next 2-10 years

1. More land and marine observations back to early 19th century, especially Southern Hemisphere and Arctic.
2. User requirements for, and applications of, reanalyses
3. Higher resolution, improved methods, other surface variables (e.g., wind, T, Tropical Cyclone position)
4. Uncertainty in forcings (e.g, CO2, solar, SST)
5. Multi-model (e.g., NASA, NCAR, NCEP, GFDL, ESRL)

Available 2014 – SIRCA

Available 2017 – include chemistry and coupling, CSIRCA

Requires international cooperation, e.g.,
Atmospheric Circulation Reconstruction over the Earth initiative

<http://www.met-acre.org>



- Summary: The Twentieth Century Reanalysis Project dataset could be used to view current atmospheric circulation patterns in a wider historical context.
- Challenges: Validating the dataset in regions of sparse observations and rapid change, e.g., the Arctic.
- Contact :
 - Jeffrey.S.Whitaker@noaa.gov
 - compo@colorado.edu



Extra Slides

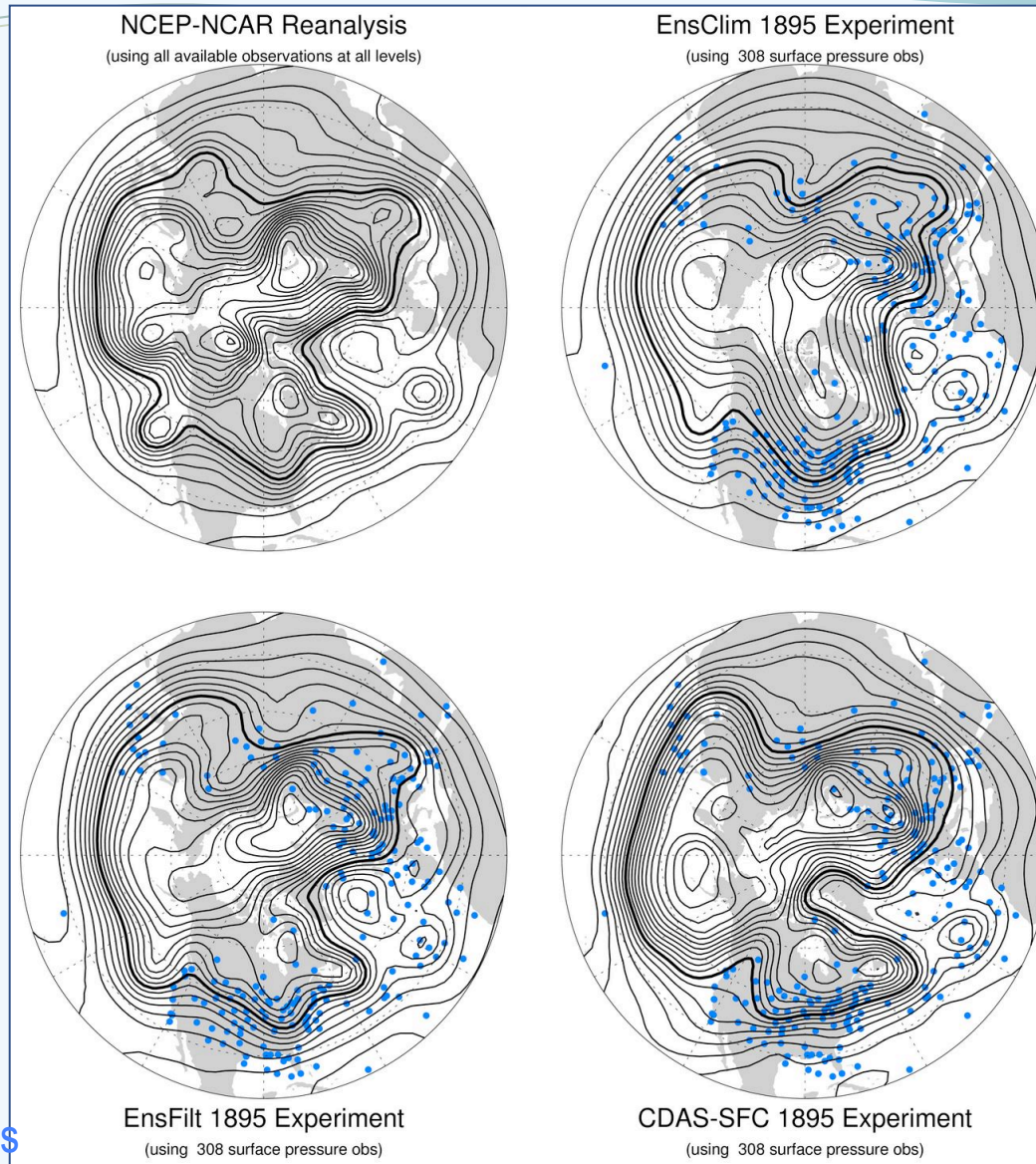


Feasibility of Surface Pressure-based Reanalysis

500mb Height Analyses for 20 Dec 2001 0Z

Full CDAS
(120,000+ obs)

EnsFilt 1895
(308 surface
pressure obs)
RMS = 49 m
Blue dots show
surface pressure
observation locations



EnsClim 1895
(308 surface
pressure obs)
RMS = 96 m

CDAS-SFC 1895
(308 surface
pressure obs)
RMS = 96 m
5500 m contour
is thickened



Co-authors on 20th Century Reanalysis Project

- **Gilbert P. Compo**, co-Lead Twentieth Century Reanalysis Project, CU/CIRES, Climate Diagnostics Center & NOAA ESRL/PSD
- **Jeffrey S. Whitaker**, co-Lead Twentieth Century Reanalysis Project, NOAA ESRL/PSD
- **Prashant D. Sardeshmukh**, CU/CIRES, Climate Diagnostics Center & NOAA ESRL/PSD
- **Nobuki Matsui**, CU/CIRES, Climate Diagnostics Center & NOAA ESRL/PSD
- **Robert J. Allan**, ACRE Project Manager, Hadley Centre, Met Office, United Kingdom
- **Xungang Yin**, STG Inc., Asheville, NC
- **Byron E. Gleason, Jr.**, NOAA National Climatic Data Center
- **Russell S. Vose**, NOAA National Climatic Data Center
- **Glenn Rutledge**, NOAA National Climatic Data Center
- **Pierre Bessemoulin**, Météo-France
- **Stefan Brönnimann**, ETH Zurich
- **Manola Brunet**, Centre on Climate Change (C3), Universitat Rovira i Virgili
- **Richard I. Crouthamel**, International Environmental Data Rescue Organization
- **Andrea N. Grant**, ETH Zurich
- **Pavel Y. Groisman**, University Corporation for Atmospheric Research & NOAA National Climatic Data Center
- **Philip D. Jones**, Climatic Research Unit, University of East Anglia
- **Michael Kruk**, STG Inc., Asheville, NC
- **Andries C. Kruger**, South African Weather Service
- **Gareth J. Marshall**, British Antarctic Survey
- **Maurizio Maugeri**, Dipartimento di Fisica, Università degli Studi di Milano
- **Hing Y. Mok**, Hong Kong Observatory
- **Øyvind Nordli**, Norwegian Meteorologisk Institutt
- **Thomas F. Ross**, NOAA Climate Database Modernization Program, National Climatic Data Center
- **Ricardo M. Trigo**, Centro de Geofísica da Universidade de Lisboa, IDL, University of Lisbon
- **Xiaolan L. Wang**, Environment Canada
- **Scott D. Woodruff**, NOAA Earth System Research Laboratory, Physical Sciences Division
- **Steven J. Worley**, National Center for Atmospheric Research



Publications using the Twentieth Century Reanalyses

Brönnimann, S., A. Stickler, T. Griesser, A. M. Fischer, A. Grant, T. Ewen, T. Zhou, M. Schraner, E. Rozanov, and T. Peter, 2009: Variability of large-scale atmospheric circulation indices for the Northern Hemisphere during the past 100 years. *Meteorol. Z.*, 18, 365-368, DOI: 10.1127/0941-2948/2009/0392.

Giese B.S., G.P. Compo, N.C. Slowey, P.D. Sardeshmukh, J.A. Carton, S. Ray, and J.S. Whitaker, 2009: The 1918/1919 El Niño. *Bull. Amer. Meteor. Soc.*, in press, DOI: 10.1175/2009BAMS2903.

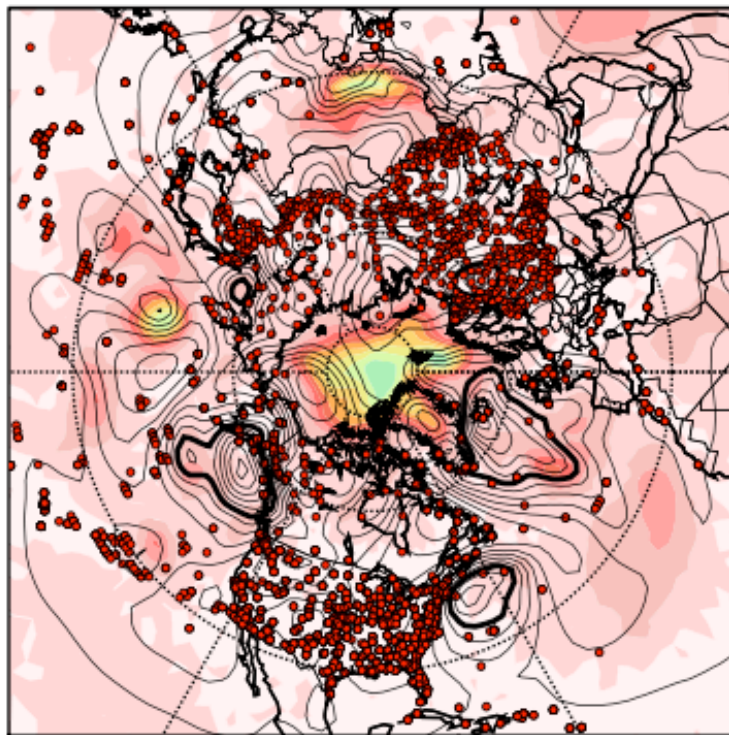
Whitaker, J.S., G.P. Compo, and J.-N. Thepaut, 2009: A comparison of variational and ensemble-based data assimilation systems for reanalysis of sparse observations. *Mon. Wea. Rev.*, 137, 1991-1999.

Wood, K. R., and J.E. Overland, 2009: Early 20th century Arctic warming in retrospect, *Intl. J. Clim.*, in press, DOI: 10.1002/joc.1973.

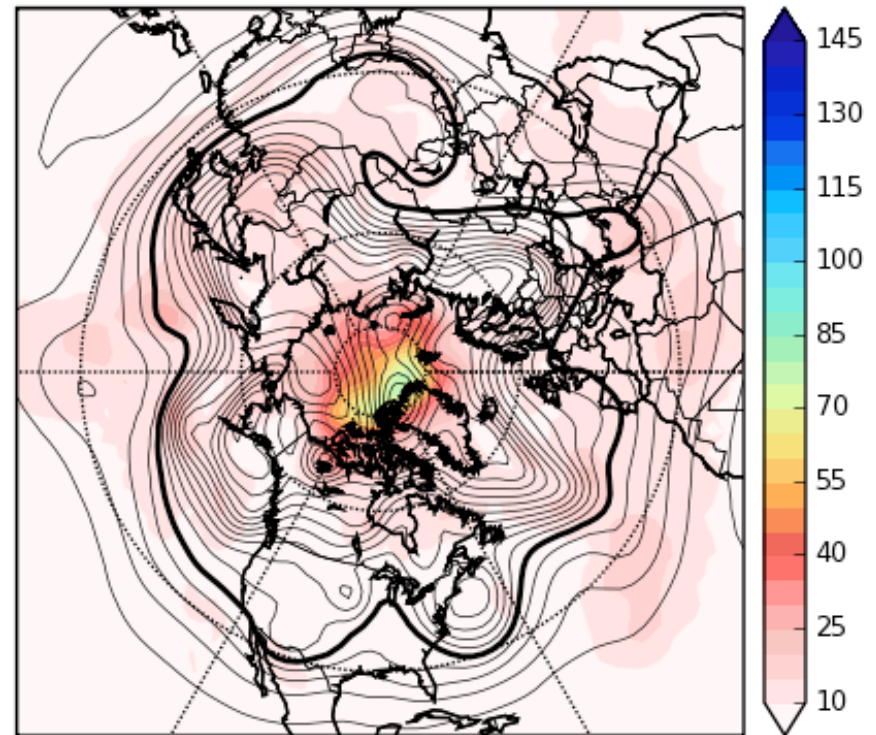


Analysis Ensemble Mean and Spread on 1 December 1945

SLP



500 hPa GPH



Sea Level Pressure

Contours- ensemble mean

Shading- blue: more uncertain, white: more certain

500 hPa Geopotential Height



Local Anomaly Correlation of Twentieth Century Reanalysis (20CR), NCEP-NCAR Reanalysis (NNR), and ERA40 twice-daily geopotential height anomalies (1958)

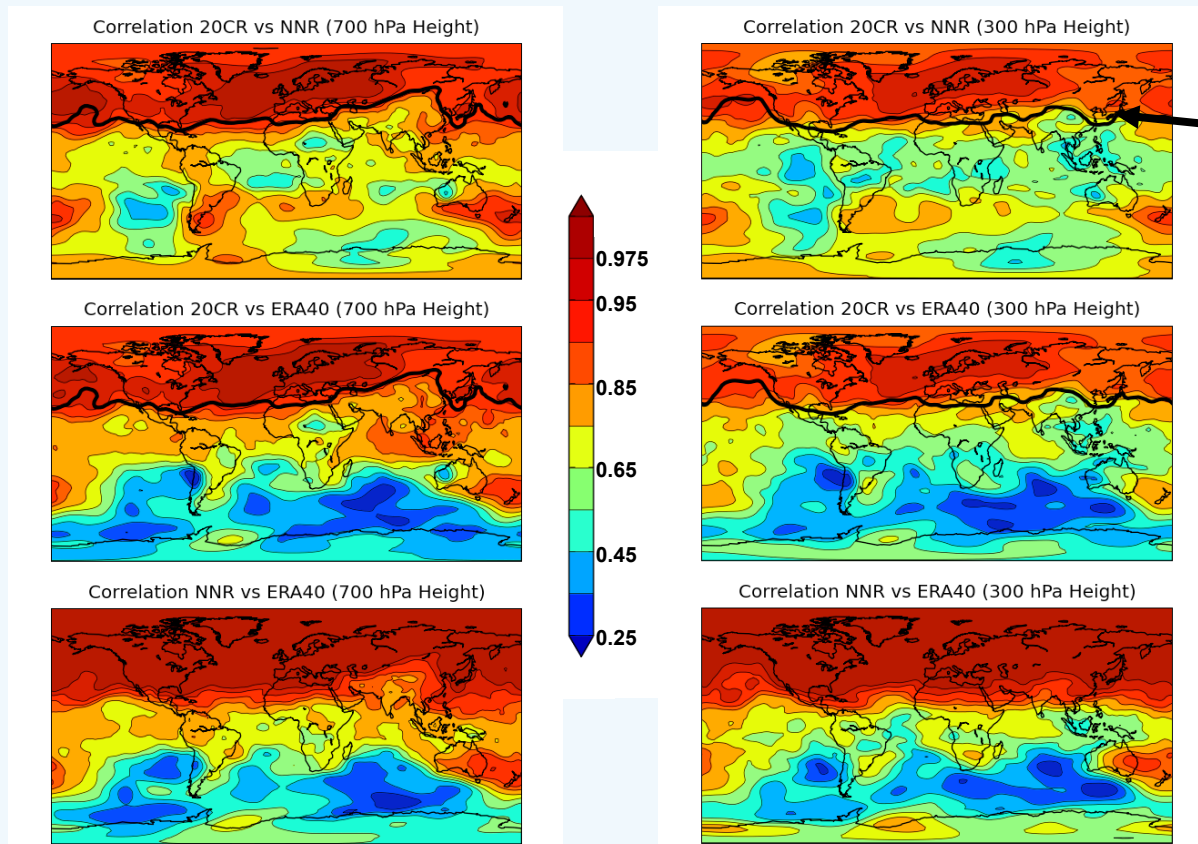
700 hPa

300 hPa

20CR
vs. NNR

20CR
vs. ERA40

NNR
vs. ERA40



0.975
correlation
between
NNR and
ERA40

Southern
Hemisphere
agreement
with ERA40
is poor.

Northern Hemisphere agreement is excellent.
Southern Hemisphere agreement is moderate to poor.
Is 20CR useful in Southern Hemisphere?

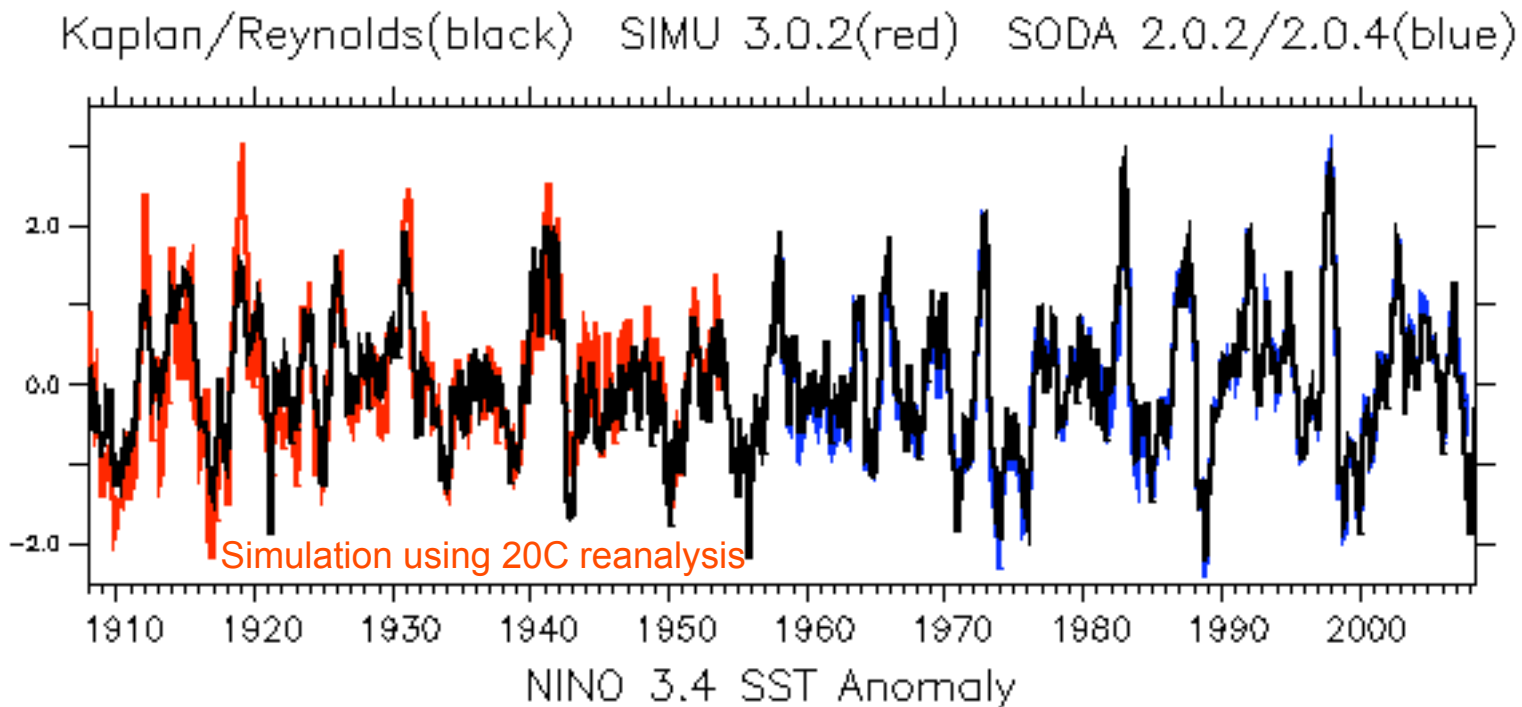


Tropical Validation

- Force global Parallel Ocean Program (POP) with daily 20th Century (1908-1956) reanalysis fields
 - 2m Air Temperature
 - 2m Specific Humidity
 - Downwelling Shortwave at Surface
 - Total cloud cover
 - 10 m Wind Speed
 - Precipitation
 - Zonal and Meridional Wind Stress
- (Giese et al. BAMS 2009)*



Nino3.4 Time series from Kaplan SST, POP Simulation, SODA Data Assimilation

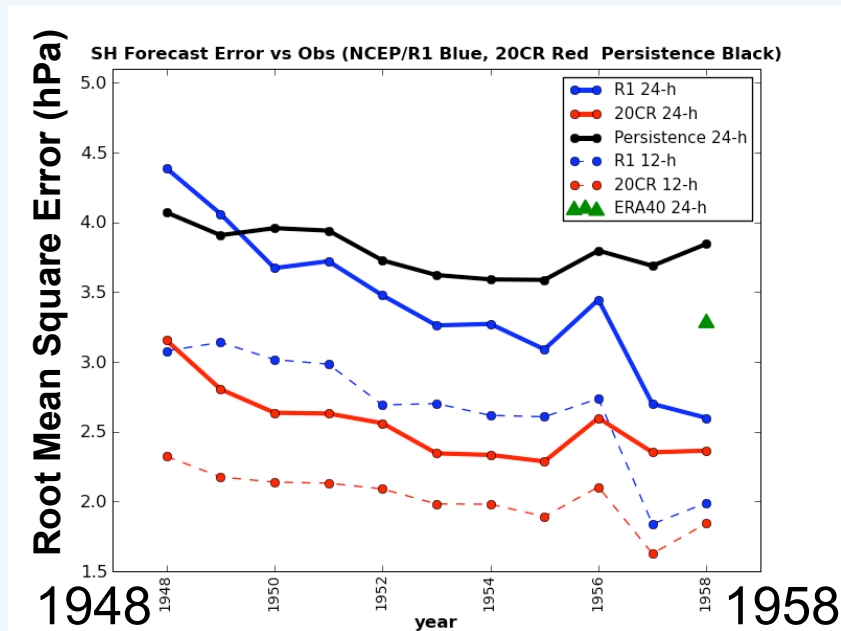


+20th Century reanalysis forcing fields **with no adjustment**
generate realistic Nino3.4 variability in simulation
+Encouraging for Ocean and Coupled Data Assimilation.
(Giese et al. BAMS 2009)

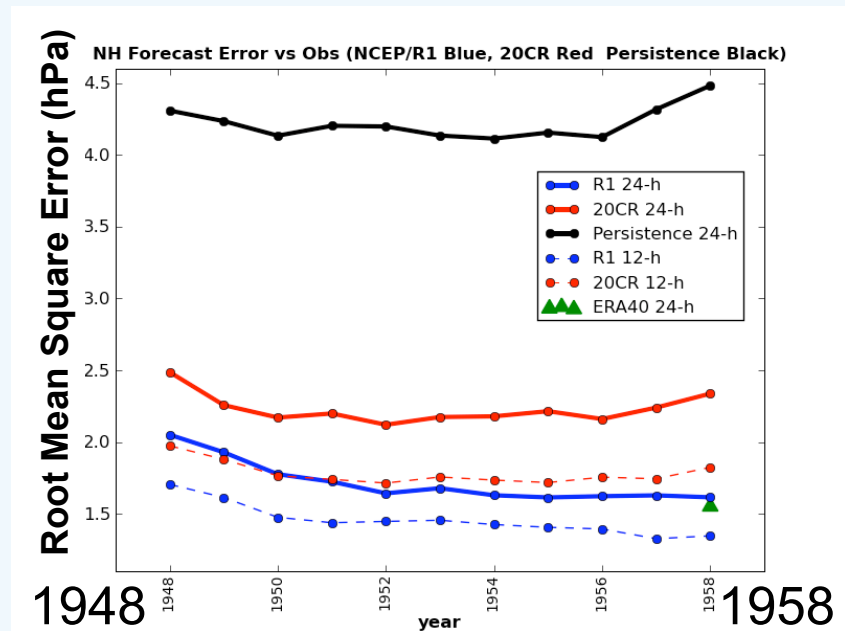


12 and 24 hour Root Mean Square difference of Marine Observations and Forecasts from NCEP-NCAR Reanalysis, Twentieth Century Reanalysis, and ECMWF Reanalysis Archive 40 (1948-1958)

Southern Hemisphere



Northern Hemisphere



Substantially better skill for 20CRv1 than for NCEP-NCAR Reanalysis or ERA40 in southern hemisphere despite the lack of upper-air observations.



20th Century Reanalysis Version 2

- Atmospheric model upgrade to experimental NCEP Global Forecast System (GFS2008ex), T62L28 (~2 degree latitude by longitude)
- GFS2008ex includes NOAH land model, and time-varying CO₂, solar variability, and volcanic aerosols
- Additional surface and sea level pressure observations from ships and stations through ACRE, NOAA CDMP, and other partners
- All Australian observations at the correct time.
- Dataset will span 1871 to present when completed.



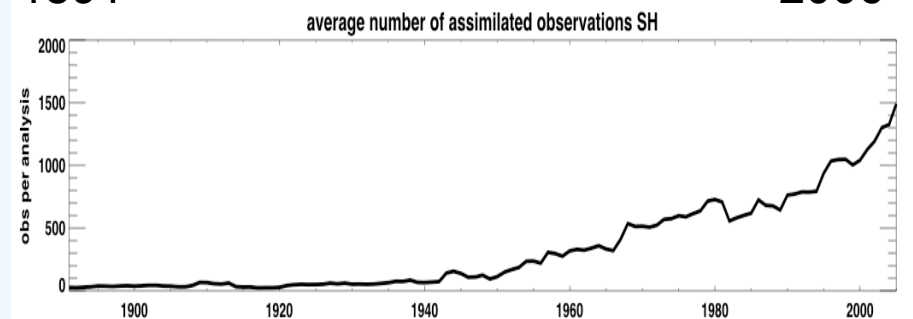
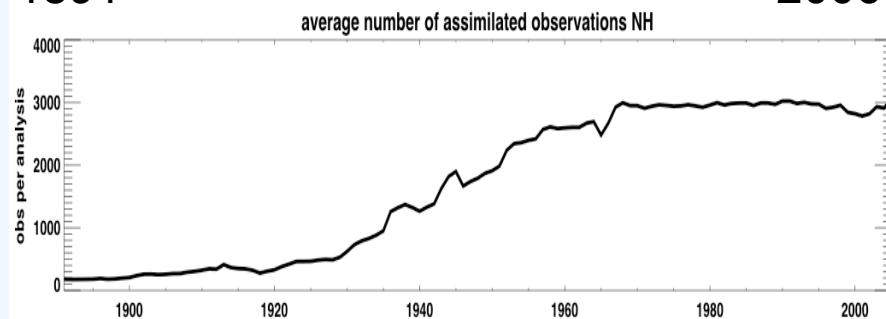
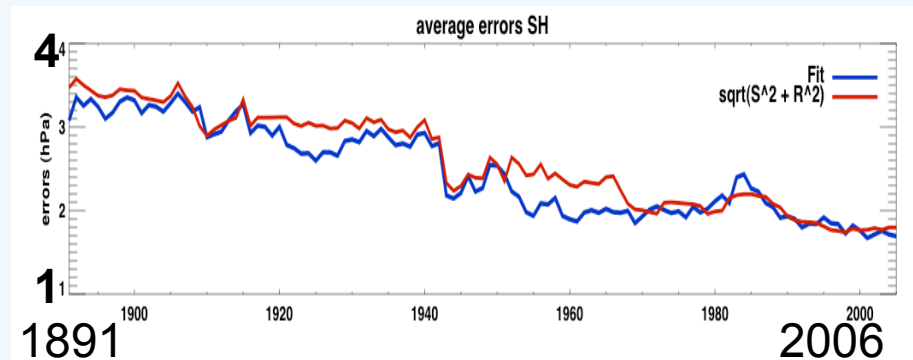
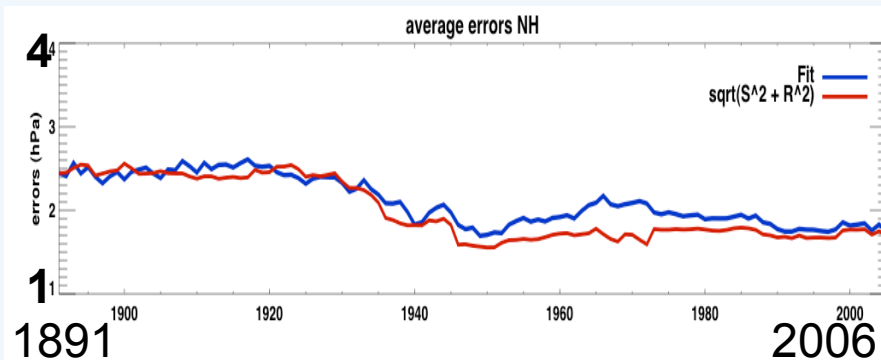
Surface Pressure uncertainty estimate poleward of 20(S,N)

blue actual RMS difference between first guess and observations

red expected difference

Northern Hemisphere

Southern Hemisphere

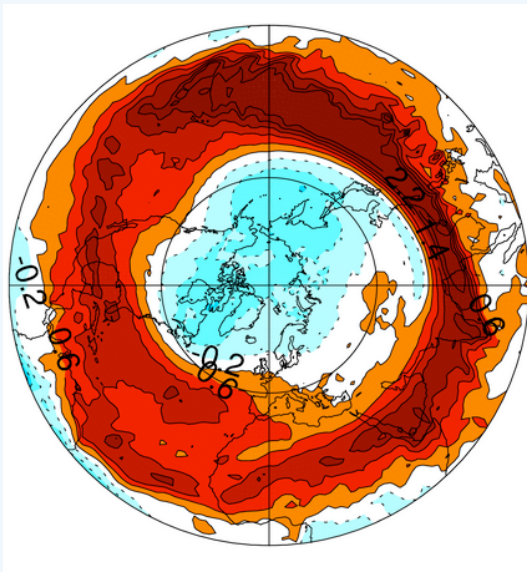


Uncertainty estimates are consistent with actual differences between first guess and pressure observations even as the network changes over more than 100 years!

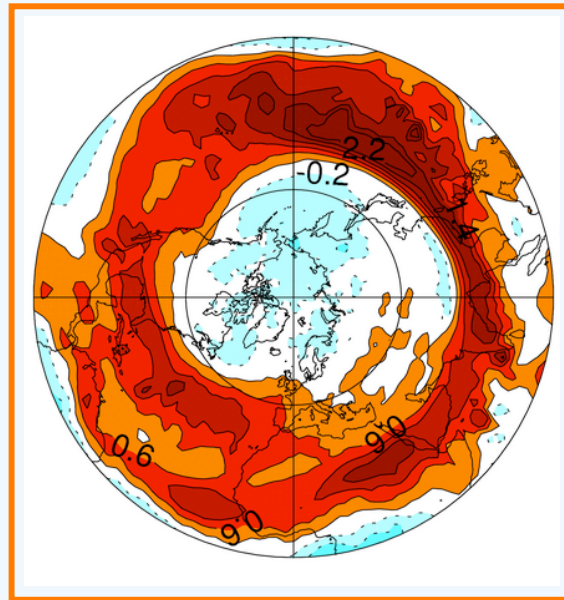


Storm Track

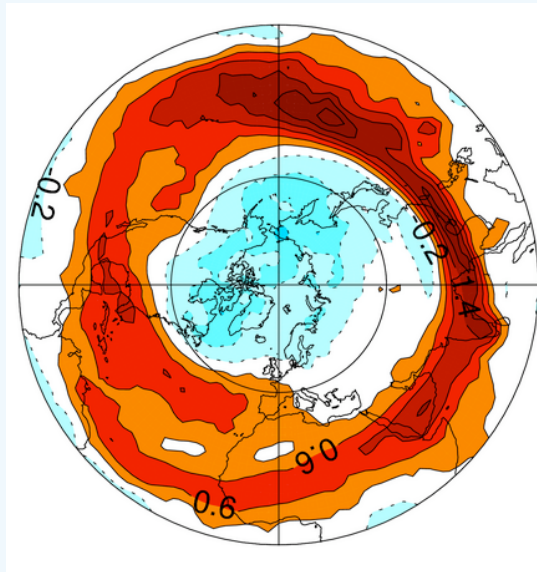
Skewness of Northern Hemisphere 250 hPa *daily* Vorticity (Dec-Feb) 1989/90-2005/06



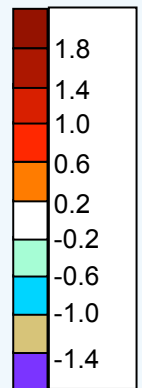
ERA Interim (~50km)
Uses satellite data



20CRv2 (~200km)
Surface pressure only



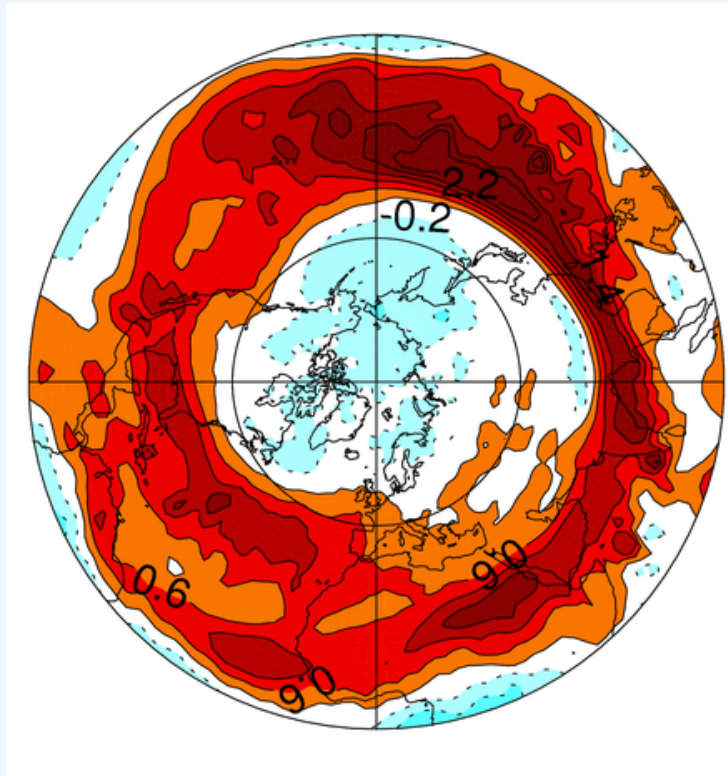
NCEP-NCAR (~200km)
Uses satellite data



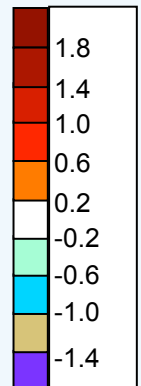
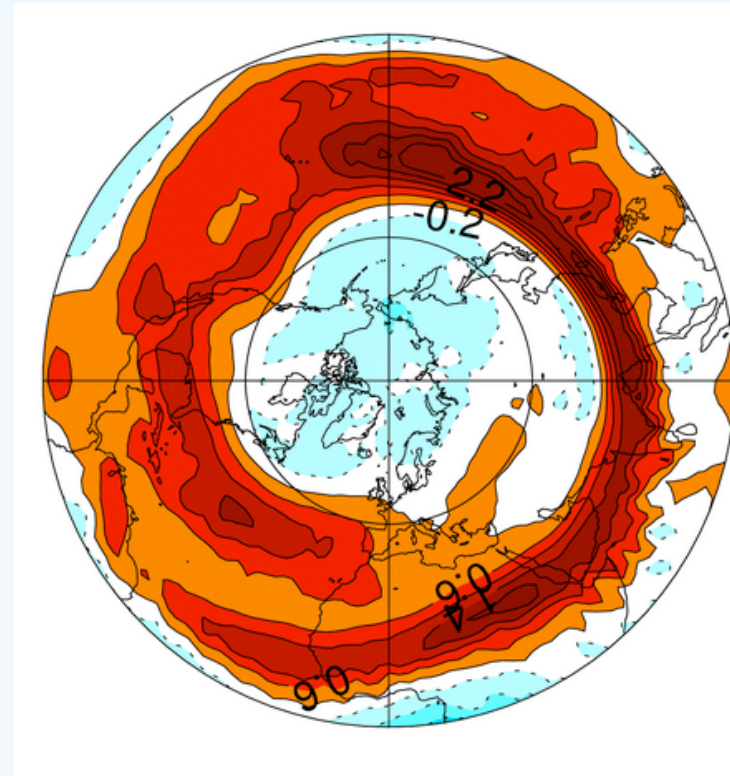


Skewness of 250 hPa Vorticity from 20th Century Reanalyses

DJF 1989/90-2005/06



DJF **1891/92**-2005/06



Storm Track Features are remarkably robust



Historical Reanalysis Status and Plans (con't)

Surface Input Reanalysis for Climate Applications (SIRCA)

SIRCA 1850-2013

- Higher resolution (T254 ~50km or higher)
- improved methods (e.g., Kalman Smoother)
- More input data (e.g., CDMP & ACRE, Zooniverse, maybe winds and T, storm position)
- latest model from NCEP (maybe multi-model, e.g., NASA, NCAR, GFDL, ESRL)
- Include uncertainty in forcings (e.g., ensemble of SSTs and Sea Ice, CO2, solar)
- Available 2014

Chemical and Surface Input Reanalysis for Climate Applications

CSIRCA 1800-2016

- Higher resolution (T382 or higher)
- improved methods (e.g., include coupled Cryosphere-Ocean-Land-Atmosphere-Chemistry system, link with NOAA CarbonTracker advances)
- More input data (e.g., ACRE-facilitated, maybe winds and T, storm position, trace gases)
- latest model from NCEP, multi-model with other models (e.g., NASA, NCAR, GFDL, ESRL)
- Available 2017

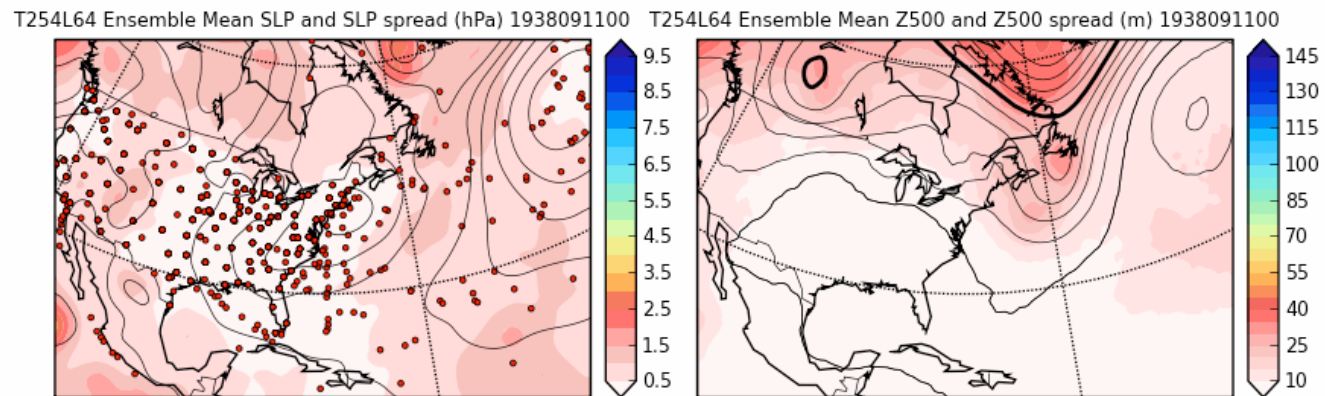


Higher resolution example of Surface Input Reanalyses for Climate Applications (SIRCA)



2008 NCEP GFS at ~50km Resolution

September 1938 New England (movie)



T254L64 (~50 km)

Is the extraordinary upper-level trough correct?

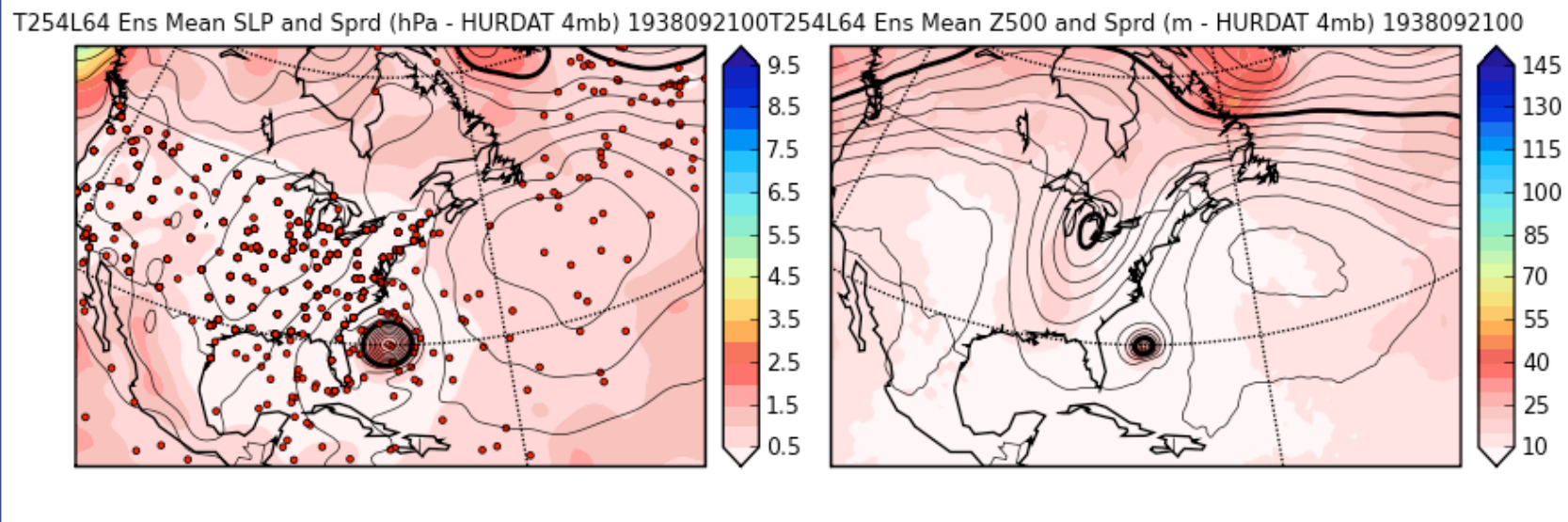


2008 NCEP GFS at ~50km Resolution

21 September 1938 00 UTC

Sea Level Pressure

500 hPa geopotential height

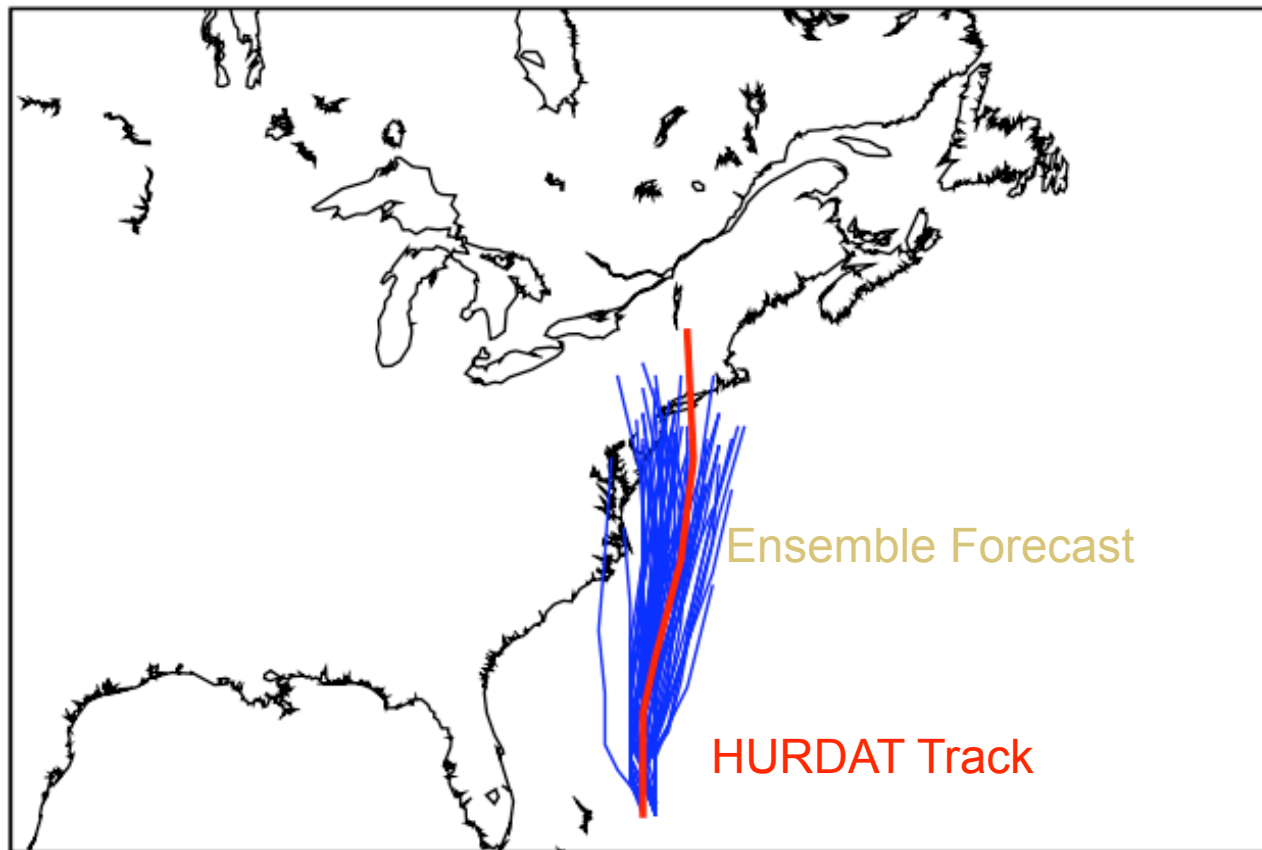


Is the extraordinary upper-level trough correct?



Any Skill Forecasting the Track?

36 hour forecast verifying 21 Sept 1938 18Z



using 56 ensemble members T254L64 (about 0.5 degree)